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A COMPENDIUM OF RADIATION SAFETY INFORMATION ABOUT PLUTONIUM

by

Frank P. Marchetti

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RADIATION SAFETY INFORMATION
ABOUT PLUTONIUM

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Frank P. Marchetti

Industrial Hygiene and Safety Division

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Most of the values presented in this publication are based on plutonium-239, because it is the most common isotope and because a large portion of the plutonium used at ANL is relatively free of penetrating isotopes. For these reasons, the primary concern here will be with the biological effects when the plutonium enters the body.

PLUTONIUM AS A HAZARDOUS MATERIAL

Introduction

Plutonium is valuable because it is a fissionable material that can be used as a reactor fuel and as a component in atomic weapons. The danger is known when it is a hazard, because large quantities of plutonium are produced by fission.

To prevent fissionable material from going into chain reaction, AEC policy requires that written control measures for preventing or limiting chain reaction be approved by the Laboratory Director for compliance to all personnel involved in the fabrication, processing, storing, transport, or other handling of such material whenever the members of any division are charged collectively with 300 g or more of Pu^{239} , Pu^{240} , Pu^{241} , or any combination thereof. To fulfill policy requirements, strict inventory procedures are mandatory.

For a criticality incident to take place, there must be a sufficient mass of fissionable material. The value of this mass depends on many

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INTRODUCTION

This publication summarizes selected radiation-safety information pertaining to plutonium and presents it in a convenient reference form for personnel working with the element.

Much of the information presented is based on the experience of the Radiation Safety Section of the Industrial Hygiene and Safety Division at Argonne National Laboratory (ANL). Also included are certain control measures and guideline values drawn from the cited items of published literature.

Most of the values presented in this publication are based on plutonium-239, because it is the most common isotope and because a large portion of the plutonium used at ANL is relatively free of penetrating radiation. For these reasons, the primary concern here will be with the hazards involved when the plutonium enters the body.

PLUTONIUM AS A HAZARDOUS MATERIAL

Criticality Hazard

Plutonium is valuable because it is a fissionable material that can be used as a reactor fuel and as a component in atomic weapons. The ability to fission makes it a hazard, because large quantities of radiation accompany each fission.

To prevent fissionable material from going into chain reaction, ANL policy requires that written control measures for preventing accidental criticality be approved by the Laboratory Director for compliance by all personnel involved in the fabrication, processing, storing, transfer, or other handling of such material whenever the members of any division are charged collectively with 300 g or more of Pu^{239} , U^{233} , U^{235} , or any combination thereof. To fulfill policy requirements, strict inventory procedures are mandatory.

For a criticality incident to take place, there must be a critical mass of fissionable material. The value of this mass depends on many

factors, rather than any single item. It suffices for this presentation to list some of the basic plutonium-239 values in tabular form (see Table I). If the minimum critical value is not exceeded, a criticality cannot occur.

Table I⁽¹⁾

VALUES OF BASIC NUCLEAR PARAMETERS FOR Pu²³⁹

	<u>Recommended Value</u>	<u>Minimum Critical Value</u>
Mass, kg		
Solution	0.22	0.51
Metal	2.6	5.6 alpha phase
	3.5	7.6 delta phase
Diameter of infinite cylinder, in.		
Solution	4.2	4.9
Metal	1.4	1.7 alpha phase
	1.8	2.1 delta phase
Thickness of infinite slab, in.		
Solution	0.9	1.3
Metal	0.18	0.24 alpha phase
	0.22	0.28 delta phase
Solution volume, liters	3.4	4.5
Chemical concentration of aqueous solution, g (of isotope)/liter	6.9	7.8

Since a criticality accident can cause fatalities and/or widespread contamination, extreme care must be exercised not to exceed, in any facility, the recommended mass values listed in Table I.

External-radiation Hazard

Plutonium is produced by irradiating uranium with neutrons in a nuclear reactor. Its isotopic composition depends on the time in the reactor and the type of reactor. The amount of beta, gamma, and neutron activity emanating from a specific quantity of plutonium depends on its isotopic composition and age. Therefore, the precautions necessary to prevent exceeding the external exposure limits vary from almost none, for very pure Pu²³⁹ with its weak x-rays having an effective energy of 17 keV, to severe, for plutonium rich in the 240 and 241 isotopes,^(2,3) and/or contaminated by fission products and daughter products.

The assessment of the beta-gamma hazard is usually made by surveying the material with a beta-gamma portable (Geiger-Muller) type or ionization chamber type survey meter.

The Maximum Permissible Dose (MPD), to the whole body, recommended by the National Committee on Radiation Protection is not more than 3 Rem (one Rem is the equivalent of a Roentgen in some instances but encompasses the radiation dose received from ionizing radiation other than gamma and x-ray) in any 13 consecutive weeks. The limit placed on the accumulated dose to radiation workers is expressed by the equation $MPD = (N - 18)5$ Rems, where N is the age of the worker.^(4a) From the equation, it can be seen that an average dose of 5 Rems/yr is permissible and that occupational exposures should be restricted to persons more than 18 yr old.

Neutron Hazard

Plutonium-239, which has a specific activity of 6.17×10^{-2} C/g (16.2 g/C), decays by alpha emission. The alpha particle has an average energy of 5.15 MeV. The alpha particles may react with certain nuclei to produce neutrons via the alpha-neutron (α, n) reaction. In fact, a mixture of Pu-Be is often used as a neutron source. When working with plutonium in association with low-atomic-number elements, such as fluorine, one should remember that a neutron hazard may exist.

The assessment of the neutron hazard is made by surveying the material with a "long counter." The long counter consists of a moderated BF₃ tube and scaler, calibrated with a neutron source of known strength.

A 40-hour exposure to a neutron flux of 18 neutrons/sec/cm² of 1 MeV energy is equivalent to a dose of 100 mRem.^(4b) The neutrons produced by a plutonium fluorine mixture have an energy of slightly more than 1 MeV.

Alpha-particle Hazard

The Pu²³⁹ alpha particle has a range of about 3.7 cm in air, and 40 μ in water and soft tissue.^(5,6) This energy is not sufficient to penetrate the body's 70- to 150- μ layer of protective skin.^(5,7) An alpha particle must have an energy of at least 7.5 MeV to penetrate a layer of protective skin 70 μ thick.⁽⁷⁾ Because of its relative inability to penetrate, the alpha particle usually is harmless as long as the alpha emitter is outside the body.

Internal Hazards

Plutonium-239 becomes a biologically hazardous material once it enters the body because of its following characteristics.

Alpha Emitter. Internally the alpha emitter can do great harm, because alpha particles have a high specific ionization and can damage a large percentage of the cells that are close to the alpha emitter.

Bone Seeker. As much as 20% (depending on particle size, solubility, chemical form, etc.) of the plutonium that enters the body by inhalation may be deposited in the bone marrow, a blood-forming organ.⁽⁸⁾

Biological Half-life. Pu^{239} has a biological half-life of about 200 yr and a low excretion rate. In 50 yr, an individual would be expected to have eliminated only 17.6% of the originally assimilated plutonium.⁽⁹⁾

Physical Half-life. The physical half-life of Pu^{239} is 24,360 yr.

Specific Activity. The specific activity of Pu^{239} is 6.17×10^{-2} C/g or 16.2 g/C. One μg of Pu^{239} will emit 1.37×10^5 alpha particles/min.

Maximum Permissible Body Burden

"The maximum permissible body burden may be defined as the maximum amount of material that can be maintained indefinitely in the adult human body without producing significant bodily injury to any person at any time during his natural life."⁽⁹⁾ The body burden for Pu^{239} , as set by the National and International Commissions on Radiological Protection, is $0.04 \mu\text{C}$ ($8.9 \times 10^4 \text{ d/m} = 0.65 \mu\text{g}$). The figure was determined by comparing the Pu^{239} radiotoxicity with Ra^{226} through animal studies. The maximum permissible body burden for Ra^{226} ($0.1 \mu\text{C}$) was determined after a study of the radiotoxicological information gained from the unfortunate experience of workers in the luminous-dial industry, and of people who consumed radium-rich water for therapeutic value in the early part of this century.

MODES OF ENTRY INTO THE BODY

Because of the low maximum permissible body burden, plutonium must be kept from entering the body. The possible modes of entry are: (1) inhalation, (2) ingestion, (3) injection, and (4) absorption. Therefore, to effectively control the health hazards of plutonium, (1) it must be kept out of the air the worker breathes, (2) it must be kept away from food and drink, (3) it must be prevented from penetrating the skin via contaminated objects capable of inflicting wounds, and (4) it must not be handled with bare hands, particularly if open wounds are present.

The remainder of this discussion is devoted to a detailed consideration of the four controls just mentioned. The controls, rules, and regulations

are effective means of safety only insofar as the individual employee observes them. The Primary Responsibility for Safety is Always with the Individual!

Inhalation

The most effective means of reducing the probability of plutonium inhalation is by containment, i.e., preventing the plutonium from becoming airborne. The quantities of plutonium and the physical state of the plutonium dictate the precautions that must be taken. With small quantities of plutonium, simple air-flow patterns may provide effective containment. For example, it is possible, under certain conditions, to work safely with small quantities of plutonium in solution in an open-faced hood. There should be an air flow of from 125 to 150 lineal ft/min passing into the open hood,^(10,11,4c) and the experimenter should wear surgical gloves and a lab coat. For larger quantities of plutonium, the ventilated glovebox has become the standard tool of the plutonium worker. Since the variables are many, the decision to use a glovebox or an open hood should be discussed with a Radiation Safety Section representative.

Radiation Safety personnel make frequent surveys of work areas to measure the effectiveness of the containment procedures. If an individual feels that plutonium has escaped its containment, he should immediately call Radiation Safety personnel to survey the area and his person. To prevent excessive spread of contamination, he should move only as far as necessary to escape the inhalation hazard and make the phone call.

Whenever a room atmosphere is known or suspected to be contaminated with plutonium, or is in danger of becoming so, respiratory protection should be used. Supplied-air equipment is preferable to the assault mask or cartridge respirator.

RCG in Air. The RCG/40 (radioactivity concentration guide for 40-hour week) for Pu^{239} is $2 \times 10^{-12} \mu\text{C/cc of air}^{(8)}$ (4.4 d/m/M^3). It represents that concentration of Pu^{239} in air in which man may work 40 hr/week for 50 weeks/yr for 50 yr and not exceed a maximum permissible body burden. Specifically, for Pu^{239} , if a "standard" man began working at age 18, at age 68 he would have $0.04 \mu\text{C}$ of Pu^{239} fixed in his body, and his "standard" skeleton would be receiving a dose rate of about 560 mRem/week.⁽⁸⁾ (The "standard" man for purposes of calculation is simply a hypothetical individual with specified dimensions, weight, water content, breathing rate, excretion rate, etc.)

In short, the RCG/40 simply refers to an average concentration of airborne activity in which a man could work and expect to retire without occupational disability from plutonium. About the same quantity of plutonium

would be inhaled during a one-hr exposure to 520 x RCG/40 as a 520-hr exposure at 1 RCG/40. The implication is that an employee exposed to air contaminated to a level of 520 times the RCG value for one hr could safely return to plutonium work after 13 weeks of no exposure. In actual practice, exposures from other sources must be considered; the art of air sampling is not sufficiently exact to permit manipulation of exposures as discussed above. It is, therefore, good practice to keep exposures to the lowest practical level.

It has been estimated, by extrapolating data obtained from animal studies, that an adult human with a lung absorption of from 1 to 10% would have to inhale from 0.2 to 2 g (from 12 to 120 mC) of plutonium of optimum particle size, for lung retention, to produce a 50% probability of death in 30 days.⁽⁹⁾ Only during an accident of catastrophic magnitude would an individual be exposed to conditions causing him to inhale such large quantities.

Lung Retention versus Particle Size. In breathing, air is drawn in through the nose, down through the trachea, through the bronchial tubes, and finally into the alveoli. In the alveoli, some of the oxygen in the air is exchanged for carbon dioxide. Since natural air contains dust, nature has provided moisture and hairs in the nostrils. The moisture acts as a glue, the hairs as a filter, in the removal of particles of dust from the air. Nature has also provided cilia, hairlike organs protruding from the wall of the trachea. Particles of from 5 to 10 μ in size are deposited in the upper respiratory tract and are quickly moved up the trachea by the ciliary action and subsequently swallowed. The efficiency of the ciliary action falls off rapidly for particles smaller than 5 μ .⁽¹²⁾ Depending on solubility and other factors, a portion of the plutonium that is deposited in the lung is transferred by the blood to other parts of the body, especially the bone and liver.

Air Sampling. To evaluate the airborne contamination in room air, the kind and concentration of radionuclides present must be known. This is done by means of air samples. An air sample is taken by passing a known volume of air through a filter paper. The particulate matter in the air is collected on the filter paper and counted. HV-70 (Hollingsworth & Vose) filter paper is usually used. The HV-70 paper usually used is 9 mils thick and has an efficiency of about 98% against dioctyl phthalate (DOP) at the lineal velocity (about 42 ft/min) at which the air passes through the filter paper.⁽¹³⁾ DOP is frequently used in determining filter efficiencies, because it has a uniform particle size of 0.3 μ .

For statistical reasons, the usual air sample consists of passing at least 10 cu M of air through filter paper. The filter paper is then removed from the air sampler and placed in a radioactivity counting probe affixed to a scaler. An immediate 5-minute α and $\beta\gamma$ count is taken, and the appropriate calculations performed. The resulting numbers are discussed in the paragraphs immediately following.

(A) Naturally occurring airborne activity. In evaluating the airborne hazard, allowances must be made for naturally occurring airborne activity, almost exclusively radon and thoron plus their daughters. The background count due to radon and thoron daughters varies from day to day and from hour to hour, depending upon meteorological conditions. It has been known to vary by a factor of 10 or more in a 24-hr period. This variable background makes it difficult to assay an air sample for plutonium immediately, since the α background levels may be 50 to several hundred times the permissible plutonium levels.

Radon (Rn^{222}) is the daughter of radium-226. Radium in very small quantities can be found over most of the earth's crust. Radium decays radioactively into radon, a chemically inert gas whose half-life is 3.825 days. The Rn^{222} diffuses into the atmosphere, where it is moved by the winds. When radon decays, it forms radioactive particles which adhere to dust in the air. During air sampling, these particles are collected and give a variable background count. The daughters of radon have an apparent half-life of about 35 minutes.⁽¹⁴⁾ After about 7 half-lives, or about 4 hours, the radon daughters decay to insignificance.

Thoron (Rn^{220}) is a daughter in the thorium-232 decay chain. Thoron has a half-life of 54.5 seconds. Even though the thorium content of the earth's surface is considerably larger than that of radium, the shortness of the thoron half-life prevents large quantities of it from diffusion into the atmosphere. Therefore, the quantity of thoron in the air is usually much less than that of radon. The thoron daughters are collected in the air sample in the same manner as the radon daughters. The apparent half-life of the thoron daughters is 10.6 hours.⁽¹⁴⁾ In this case, 7 half-lives amount to 3.1 days.

(B) Alpha-beta-gamma factor. An attempt has been made to assay air samples with only an immediate count through the use of the "alpha-beta-gamma factor." The "alpha-beta-gamma factor" is defined as follows:

$$\alpha\beta\gamma \text{ factor} = \frac{\beta\gamma \text{ d/m/M}^3}{\alpha \text{ d/m/M}^3}.$$

The $\alpha\beta\gamma$ factor depends on such variables as ventilation, fall-out, meteorological conditions, etc., but is usually between 1.5 and 2.8 in Building 205 at ANL.

Data presented in NBS Handbook 51^(4d) show the amount of radon accumulated in air samples as a function of sample collecting. The data show that a sample of longer than 20 min has a ratio of about 1.7 beta-gamma to alpha activity. For almost every air sample taken at ANL, the

$\alpha\beta\gamma$ factor is calculated. If the factor is significantly less than 1.5, the sample probably contains a long-lived alpha-emitting radionuclide. If the factor is significantly greater than 2.8, there is a high probability that the air contains a beta-gamma active radionuclide other than the radon-thoron daughters.

In evaluating an air sample, the first count is made minutes after the sampling stops. If the first count has an $\alpha\beta\gamma$ factor that indicates long-lived activity in the air, the sample is recounted one-half hour later. If the sample does not decay according to the radon decay curve, it can be assumed there is activity in the air other than radon plus daughters.

(C) Constant Air Monitor (CAM-5). The Argonne Constant Air Monitor, Model 5 (CAM-5), presents on three recorders sufficient information, if properly interpreted, to immediately assay airborne activity in the atmosphere at any given time. The three recorders give the following information:

1. The total α counts collected on the HV-70 filter paper,
2. The total $\beta\gamma$ counts collected on the HV-70 filter paper,
3. The ratio of $\alpha/\beta\gamma$ counts.

The CAM-5 operates on the principle that an equilibrium fraction is reached if the atmosphere being sampled contains only radon plus daughters. If other particulate radioactive nuclides are collected on the filter paper, the ratio will be disturbed in one direction if the contaminant is α -active, and in the other if the contaminant is $\beta\gamma$ -active. Thus, an increase or decrease of radon daughters in the atmosphere due to changing meteorological conditions can readily be interpreted as such. Because the detector is not shielded, fluctuations in the $\beta\gamma$ background must be carefully controlled. A background increase would cause the CAM-5 to react as it would if a $\beta\gamma$ -active contaminant were being collected. A background decrease would produce a reaction similar to that caused by the collection of an α -active air contaminant. In either case, an airborne hazard would be falsely indicated. However, gamma radiation changes usually are abrupt and easily recognized.

(D) Possible errors. Many variables and possible errors are associated with air sampling. For example, the usual air sample is not necessarily representative of the air that an individual working in the area has taken into his lungs. An attempt, of course, is made to place the air sampler as close to the work area as possible. Another factor that must be evaluated is that an air sample taken in a room that has been unoccupied for a considerable length of time may be different from an air sample collected after occupancy. With no one in the room, dust settles. Immediately after occupancy, movements in the room stir up the dust (with its attendant contamination) and thereby change the air-sample results. Also, the flow rate of

the air sampler is not constant, especially for very long or dusty samples. The more dust that is collected on the filter, the more resistance to the flow of air. This, in turn, will reduce the flow rate.

Ingestion

Plutonium must be kept away from food and drink to reduce the hazard of ingestion. Therefore, no food or drink should be brought into the "active area."

Strict personal hygiene must be practiced to prevent bringing contaminants (radioactive or otherwise) to the eating area. Hands should be washed. Hands and shoes should be monitored before leaving the "active area."

It has been estimated by extrapolation from animal experiments that the ingestion of about 1.5 lb of Pu^{239} would be necessary to produce death in 30 days in 50% of the cases.⁽⁹⁾ The 1.5 lb of plutonium would be about half the volume of a package of regular cigarettes. The probability of an individual unknowingly eating that much plutonium is quite small.

Alpha Surveying. Alpha particles do not penetrate matter to any appreciable extent. They are stopped by a few centimeters of air, a sheet of paper, or by thin layers of moisture, paint, dirt, or oil. For this reason, a very thin windowed counter must be placed very close to the alpha-radioactive material to detect its activity. The alpha survey instruments in use are the air-proportional, gas-proportional, and scintillation types.

(A) Air-proportional portable alpha counter. Examples of the air-proportional type of alpha survey instrument are: the ANL "Shoebox" PAC (portable alpha counter), the Pee Wee PAC, and the Eberline transistorized PAC-1A. All operate on the same principle. A potential of about 2200 V is placed on the wires in the probe. The alpha particle entering the probe ionizes the air in the probe, causing a pulse of current which is amplified, and registered as a deflection on a meter and as a click in the earphone. The window of the probe is covered by a thin membrane of Mylar (0.8 mg/cm^2) or nylon (0.2 mg/cm^2).

The lower detectable limit for routine surveying with this type of PAC is about 500 disintegrations per minute (dpm) in the area under the probe. One thousand dpm is equivalent to almost $0.008 \text{ } \mu\text{g}$ of plutonium per probe area. The instrument is usually calibrated with a spot source.

The air-proportional PAC is fickle and difficult to work with because of the high voltage on its probe. If the thin nylon windows are used, high humidity, a torn window, or the presence of organic vapors can cause

false readings. When humidity is high, some PAC's are usually inoperative. Heated alpha probes on hand and foot monitors have done much to overcome humidity problems. The probes for portable instruments can be kept warm under a heat lamp.

(B) Gas-proportional portable alpha counter. The gas-proportional type PAC's use a flow of dry propane or P-10 (10% methane, 90% argon) gas in their probes. The portable instruments (Eberline PAC-3G) use dry propane gas and aluminized Mylar screens of $\frac{1}{4}$ -mil thickness ($\sim 0.85 \text{ mg/cm}^2$). The counting gas reduces the voltage necessary on the wires in the probe to about 1500 Volts, and lowers the background noise in the earphones. The minimum detectable plutonium contamination is reduced by a factor of about 2 when compared to the air-proportional PAC. However, the gas-proportional PAC has the following disadvantages:

1. The propane gas is flammable.
2. The probe window is thicker, thereby stopping a larger percentage of the alpha particles.
3. Probe purge time is necessary before the instrument is ready for use.

(C) Personnel monitor. The instrument used in the ANL plutonium facilities primarily as a personnel monitor is the ac-operated count-rate meter, which has a large-area probe and uses P-10 as the counting gas. This personnel monitor can be used to survey hands, feet, and portable objects. Contamination is indicated by a meter deflection and by audible clicking from the attached speaker.

Whenever a hand is withdrawn from a glovebox, it should be surveyed with the personnel monitor. An individual should survey his hands and shoes whenever he leaves a plutonium work area. Frequent surveys are the surest and quickest way of revealing the presence of contamination.

(D) Alpha scintillation detector. The portable alpha scintillation detector, sometimes called "poppy," uses ZnS as a scintillator. The unit includes a probe, which is covered with light-tight aluminized Mylar; a meter, on which amplified impulses will be registered; and earphones, on which the amplified impulses can be heard. An alpha particle hitting the scintillator causes a flash of light which is transmitted to a photomultiplier tube by a plastic light pipe. When using the "poppy," a person must use extreme care to avoid making even a pinhole in the light-tight screen, because the smallest amount of light will cause a meter reading.

(E) Meaning of survey results. The notations used to indicate alpha contamination are as follows:

1. d/m per surface area (the area of the probe indicates what instrument was used to perform the survey). Examples are:
 - a) 61 cm^2 = Eberline gas-proportional (PAC-3G) and air-proportional (PAC-1A). Example: $20,000 \text{ d/m}/61 \text{ cm}^2$.
 - b) 57 cm^2 = Eberline scintillation counter (PAC-1S). Example: $20,000 \text{ d/m}/57 \text{ cm}^2$.
 - c) 440 cm^2 = Eberline floor monitor (FM-3G). Example: $2000 \text{ d/m}/440 \text{ cm}^2$.
 - d) 330 cm^2 is the area of the 10-wire probe used with the personnel monitors.
2. "M" (defined as $1000 \text{ d/m}/100 \text{ cm}^2$). Example: $5\text{M} = 5000 \text{ d/m}/100 \text{ cm}^2$.

Injection

Plutonium can enter the body by means of cuts, scratches, or other breaks in the skin. Personnel who have open cuts or sores should wear surgical gloves or finger cots while working with plutonium. Scratches, cuts, or punctures caused by plutonium or articles contaminated with plutonium should be given immediate attention.

As much of the plutonium should be removed from the wound site as possible, by bleeding and flushing the wound with large volumes of water. All such cuts that occur at ANL must be reported as soon as possible to the Radiation Safety Section of the Industrial Hygiene and Safety Division and also to the Health Division.

The best protection against injection of plutonium is the use of extreme care when working with sharp objects. If sharp objects must be used, the worker should protect himself by wearing leather gloves over the usual rubber gloves. All rough or sharp edges or burrs should be carefully filed away or taped over before handling recently cut or drilled metal.

Absorption

Plutonium can also enter the body by absorption through the intact skin.^(5,9) Data from animal studies indicate that the absorption rate increases with the acidity of the plutonium solution. Contamination is prevented by wearing surgical gloves at all times when working with plutonium, and by removing all personal contamination as soon as possible.

BIOASSAY SAMPLES

A bioassay specimen is requested about every 60 days from ANL employees who work directly with plutonium. The specimen is usually in the form of an overnight urine sample. The sample is a means of measuring an individual's body burden of plutonium, if any.

The ANL Bioassay Group uses two methods to assay plutonium in urine. The faster method is to evaporate the sample to dryness (nitric acid wet ash), dissolve the residue in acid, perform a chemical separation, and plate the plutonium on a planchet. This planchet is placed in a 2π gas-flow proportional counter and counted for at least 4 hr. This technique is sensitive to 0.5 d/m/1500 ml of urine or 3.7 pg of Pu^{239} .

An individual receiving an exposure to soluble plutonium acute enough to produce a body burden would, after 100 days, excrete plutonium at the rate of about 6 d/m/1500 ml or 44 pg/day.⁽¹⁵⁾ Under these circumstances, the foregoing analytical method could detect 10% of a body burden.

The slower but more sensitive method is as follows. After the chemical separation of the plutonium, it is electroplated on a planchet and placed in intimate contact with a piece of NTA film for 168 hours. The film is developed, and the α tracks are counted under a microscope. This method can be as much as 10 times more sensitive than the previously described method.⁽¹⁵⁾ The longer the film is exposed to the sample, the more reliable become the low-level readings within limits. A disadvantage is the length of time between the receipt of the sample and the result.

At present, if someone is exposed to plutonium, the faster method of analysis is used because results are available in about 24 hours.

MEDICAL TREATMENT

"Studies have shown that the trisodium calcium salt of diethylene-triaminepenta-acetic acid (DTPA) is the most effective agent discovered to date for increasing the urinary elimination of plutonium (Pu^{239}) from the human body."⁽¹⁶⁾ Other chemical agents that have been used to increase the plutonium elimination rate are CaEDTA (calcium disodiummethylenediaminetetra-acetic acid) and zirconium citrate.^(5,9) These agents have been known to increase the plutonium elimination rate by a factor of 10 through their chelating action.⁽¹⁷⁾

SUMMARY OF PLUTONIUM-239 PROPERTIES

Physical Properties

Among the physical properties ascribed to Pu^{239} are the following:

1. The isotope is an alpha emitter. The average energy of the alpha is 5.15 MeV.
2. The range of the alpha particle in air is about 3.7 cm.
3. The range of the alpha particle in tissue is about 40 μ .
4. The physical half-life is 24,360 yr.
5. The specific activity is $6.17 \times 10^{-2} \text{ C/g}$ (16.2 g/C).
6. In the presence of many light elements, Pu^{239} produces neutrons via an α, n reaction.
7. The smallest mass of Pu^{239} that can go critical under optimum conditions is about 509 grams in an aqueous solution.

Biological Properties

Among the biological properties of Pu^{239} are the following:

1. The isotope is a bone seeker (the bone marrow is a blood-forming organ).
2. The biological half-life is about 200 yr.
3. The permissible body burden is 0.04 μC or 0.65 μg or $8.9 \times 10^4 \text{ d/m}$.
4. The absorption into the blood stream of orally administered Pu^{239} is from 0.003 to 0.01% depending on conditions.
5. Animal experiments indicate that Pu^{239} can be absorbed through intact skin. The absorption rate seems to increase with the acidity of the Pu^{239} solution.
6. Experiments with animals indicate that from 1 to 10% of inhaled Pu^{239} may be retained, depending on particle size, solubility, etc.
7. The RCG for a 40-hr week is 4.4 d/m/ M^3 of air or 32 pg/ M^3 .
8. In Table 12 (biological and related physical constants) of the "Report of ICRP Committee II on Permissible Dose for Internal Radiation (1959),"⁽⁸⁾ the following constants are given for a "standard" man exposed to soluble Pu^{239} :
 - a) The fraction of Pu^{239} absorbed into the blood stream from the gastrointestinal tract is 3×10^{-5} .

- b) In the static condition, the fraction of soluble Pu^{239} in the bone compared to that in the total body is 0.9.
- c) During assimilation, the fraction of Pu^{239} that moves from the blood to the bone is 0.8.
- d) The fraction of Pu^{239} ingested that reaches the bone is 2.4×10^{-5} .
- e) The fraction of Pu^{239} inhaled that reaches the bone is 0.2.

SUGGESTED READING

More detailed descriptions of the physiology and toxicology of Pu^{239} are contained in items (3), (5), (9), and (18) of the accompanying list of "References."

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